Guidance, Navigation, and Control Considerations for Nuclear Thermal Propulsion

Michael G. Houts[1], Doyce P. Mitchell[2], Tony Kim[3]

The fundamental capability of Nuclear Thermal Propulsion (NTP) is game changing for space exploration. A first generation NTP system could provide high thrust at a specific impulse above 900 s, roughly double that of state of the art chemical engines. Characteristics of fission and NTP indicate that useful first generation systems will provide a foundation for future systems with extremely high performance. The role of a first generation NTP in the development of advanced nuclear propulsion systems could be analogous to the role of the DC-3 in the development of advanced aviation. Progress made under the NTP project could also help enable high performance fission power systems and Nuclear Electric Propulsion (NEP). Guidance, navigation, and control of NTP may have some unique but manageable characteristics.

Nomenclature

CFEET	=	Compact Fuel Element Environmental Test
DOE	=	Department of Energy
HAT	=	NASA Human Architecture Team
HIP	=	Hot Isostatic Press
NASA	=	National Aeronautics and Space Administration
NCPS	=	Nuclear Cryogenic Propulsion Stage
NTP	=	Nuclear Thermal Propulsion
NTR	=	Nuclear Thermal Rocket
NTREES	=	Nuclear Thermal Rocket Element Environmental Simulator
PEC	=	Pulsed Electric Current
SLS	=	Space Launch System

I. Introduction

Development efforts in the United States have demonstrated the viability and performance potential of NTP systems. For example, Project Rover (1955–1973) completed 22 high power reactor and fuel tests. Peak performances included operating at a fuel element hydrogen exhaust temperature of 2550 K and a peak fuel power density of 5200 MW/m3 (Pewee test), operating at a thrust of 930 kN (Phoebus-2A test), and operating for an accumulated time of 109 minutes (NF-1 test).[4] Results from Project Rover indicated that an NTP system with a high thrust-to-weight ratio and a specific impulse greater than 900 s could be feasible. Excellent results have also been obtained by Russia. Ternary carbide fuels developed in Russia may have the potential for providing even higher specific impulses. Cermet fuels, developed primarily for use in high performance space fission power systems, also show potential for enabling high thrust, high Isp NTP systems.

Many factors would affect the development of a 21st century nuclear thermal rocket (NTR). Test facilities built in the US during Project Rover are no longer available. However, advances in analytical techniques, the ability to utilize or adapt existing facilities and infrastructure, and the ability to develop a limited number of new test facilities may enable a viable development, qualification, and acceptance testing strategy for NTP. Although fuels developed under Project Rover had good performance, advances in materials and manufacturing techniques may enable even

[1] Nuclear Research Manager, Technology Development and Transfer Office/ZP30, Member
[2] Manager, Nuclear Thermal Propusion Project, Technology Development and Transfer Office/ZP30, Member
[3] Deputy Manager, Nuclear Thermal Propulsion, Technology Development and Transfer Office/ZP30, Member
[4] Koenig D. R. (1986) Experience Gained from the Space Nuclear Rocket Program (Rover), LA-10062-H, Los Alamos National Laboratory, Los Alamos, NM

higher performance fuels. Potential examples include cermet fuels and advanced carbide fuels. Precision manufacturing will also enable NTP performance enhancements.

NTP systems may also have certain unique guidance, navigation, and control characteristics. Understanding these characteristics will help ensure that maximum benefit is obtained from the use of NTP.

NTP will only be utilized if it is affordable. The NTP development and qualification strategy must be optimized to obtain all required data while minimizing cost through a combination of analysis, non-nuclear testing, and nuclear testing. Strategies must be developed for affordably completing required nuclear testing. A schematic of an NTP engine is shown in Figure 1.

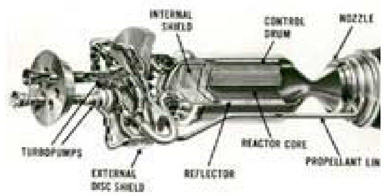


Figure 1. Schematic of an NTP Engine.

II. Attributes of NTP

NTP has several unique attributes compared to other high thrust propulsion systems. In NTP, energy comes from fission, not chemical reactions. Because the energy density of fission is seven orders of magnitude great than that of the best chemical reactions, space fission systems can often be viewed as having unlimited energy density.

The fact that NTP uses energy from fission also allows a wide range of propellant choices. Hydrogen has been proposed for use in first generation systems because its low molecular weight allows specific impulse to be maximized for a given core operating temperature. However, future NTP systems could potentially use other propellants if desired, including volatiles obtained via in-situ resource utilization.

The startup of an NTP system is relatively slow, typically requiring over thirty seconds to go from zero thrust to full thrust. In addition, the shutdown of an NTP system is relatively slow, with core power typically a few percent of operating power a few minutes after shutdown, decreasing to < 0.1% of operating power within several hours.

For some NTP engine designs, once the engine is shutdown it would not be able to be restarted for ~48 hours due to reactivity effects from a certain fission product (Xe-135).

Feedback mechanisms within the NTP engine can be complex. The reactivity of the reactor can be effected by both the presence of hydrogen and temperature. For moderated systems (e.g. the Rover/NERVA engines) the presence of hydrogen will tend to increase reactivity. Cooling of certain reactor components (such as the reflector) will also increase reactivity. The Rover/NERVA program demonstrated many aspects of NTP operation, and that NTP reactors can be designed to operate in a safe, stable manner.

III. Basic NTP Operation

The operation of a first generation NTP engine is conceptually simple. Hydrogen from a propellant tank is pumped through a solid core reactor where it is heated to high temperature (~2700 K) and exhausted through a converging / diverging nozzle to obtain a specific impulse on the order of 900 s. However, as with all rockets, the actual NTP engine will be a complex system.

A typical cross section of an NTP reactor is shown in Figure 2. The core contains a high temperature uranium-bearing fuel (proposed fuels include W/UO_2 cermet and a coated graphite composite), coolant channels (for hydrogen flow), and other components/materials as needed. The core is surrounded by a neutron reflector (typically Be) that also contains the control system. As with all nuclear reactors, the system effectively runs on a neutron balance. At steady state power, the neutrons produced by fission equal the neutrons lost to absorption or escape. If more neutrons are being produced by fission than are being lost to absorption or escape, the reactor power will be

increasing. If less neutrons are being produced by fission than are being lost to absorption or escape, the reactor power will be decreasing. Numerous factors affect the neutron balance (reactivity), including the amount of hydrogen in the core, the temperature of various reactor components, fission products, and the amount of uranium that has been lost through fission or release. Reactors can be designed (in general) to passively maintain steady-state operation. However, when additional adjustments are needed a variety of approaches can be used. The approach shown in Figure 2 uses control drums, on which an ~120 degree segment is covered with a neutron absorbing material (often B_4C). If there is a need to increase reactivity, the B_4C is rotated away from the core, reducing neutron absorption in the B_4C and allowing more neutrons to be reflected back into the core where they can potentially be absorbed in uranium and cause a fission. If there is a need to decrease reactivity, the B_4C can be rotated towards the core resulting in more neutrons being absorbed in the B_4C and fewer being available to cause fission in the uranium bearing fuel. Most control drum movement will occur during engine startup and shutdown. A relatively small amount of control drum movement will be needed during steady state operation to compensate for uranium that is fissioned, neutron absorption by the resulting fission fragments, uranium that is lost from the core due to fuel element degradation, and other factors.

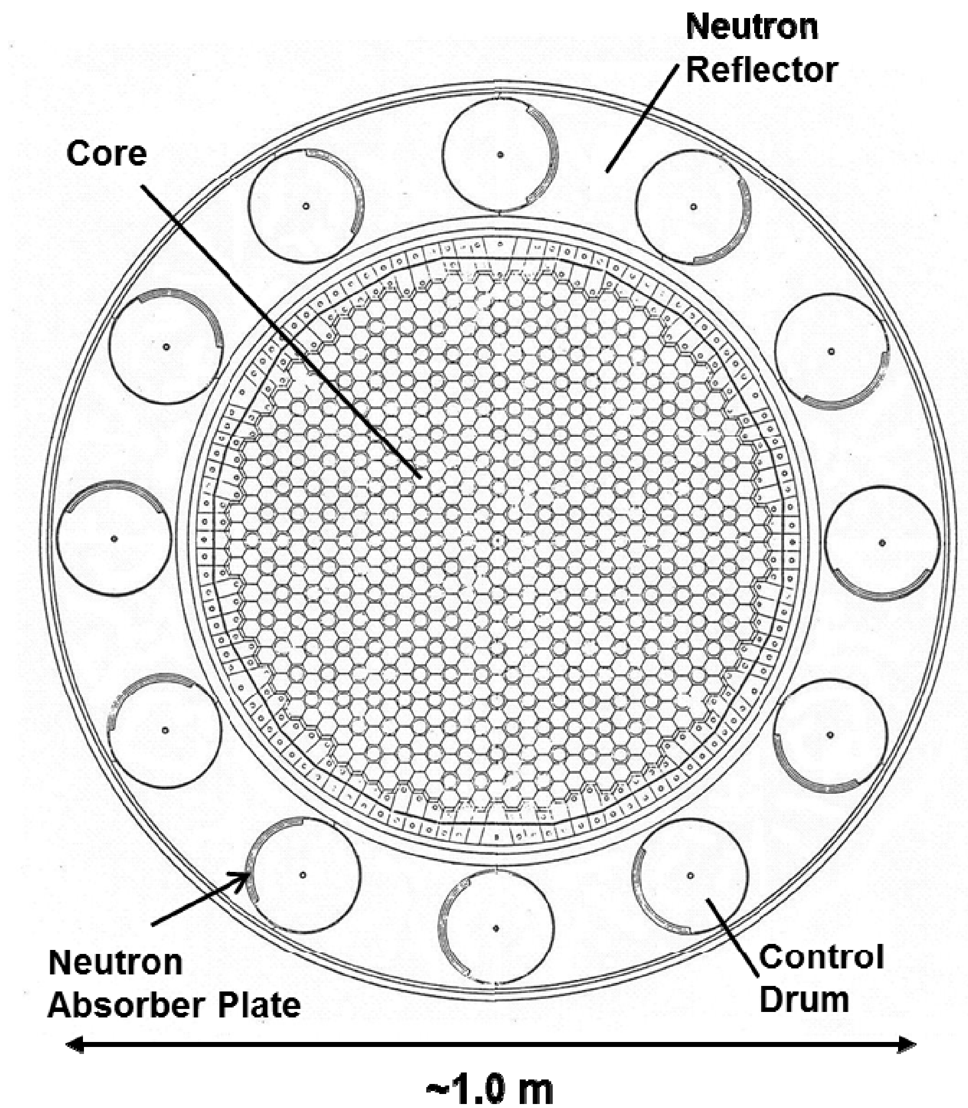


Figure 2. Representative Cross Section of an NTP Reactor

IV. NTP Guidance, Navigation, and Control

Some aspects of guidance, navigation, and control will be unique for NTP systems. However, there do not appear to be any insurmountable issues or concerns.

For example, although slow by chemical propulsion system standards, the start up of a nuclear thermal rocket is quite rapid compared to the start up of most terrestrial fission reactors. Reactivity effects from the introduction of hydrogen into the engine and temperature changes within the engine will need to be compensated for by rotation of external control drums. Depending on NTP engine design, the nested control loops utilized for NTP operation could be very complex.

The relatively slow startup and shutdown of NTP will also require that slow changes in thrust at the start and end of a burn be taken into account in a way the allows propellant to be used as efficiently as possible. There may also be deviations between the predicted thrust as a function of time and the actual thrust as a function of time.

Second generation (or beyond) NTP systems may incorporate electric propulsion at some level, using energy from the reactor to power electric thrusters. This “bimodal” operation may also have unique guidance, navigation, and control characteristics.

As NTP designs mature, guidance, navigation, and control issues should be addressed to ensure maximum mission benefit from the NTP system.

V. Ongoing Work Related to NTP Technology Development

A. Development of a High Power (~1 MW input) Nuclear Thermal Rocket Element Environmental Simulator

A high temperature, high power density fissile fuel form is a key technology for NTP. Fuel life and performance is largely limited by mass loss in a hot gas/cyclic environment. Hence a major milestone of the NTP project is the completion and initial utilization of the 1-MW Nuclear Thermal Rocket Element Environmental Simulator (NTREES) test chamber. The purpose of the NTREES facility (which also includes an arc heater and the Compact Fuel Element Environmental Tester, CFEET) is to perform realistic non-nuclear testing of nuclear thermal rocket (NTR) fuel elements and fuel materials. Although the NTREES facility cannot mimic the neutron and gamma environment of an operating NTR, it can simulate the thermal hydraulic environment within an NTR fuel element to provide critical information on material performance and compatibility.

The NTREES upgrade is nearing completion, and it is already being utilized to test fuel elements at near-prototypic operating temperatures with several hundred kW of input power. Once fully operational, the 1-MW NTREES test chamber will be capable of testing fuel elements and fuel materials in flowing hydrogen at pressures up to 1000 psi, at temperatures up to and beyond 3000 K, and at near-prototypic reactor channel power densities. NTREES will be capable of testing potential fuel elements with a variety of propellants, including hydrogen with additives to inhibit corrosion of certain potential NTR fuel forms; however the focus of FY 2015 activities has remained on pure hydrogen propellants.

The NTREES facility is licensed by the Nuclear Regulatory Commission (NRC) to test fuels containing depleted uranium. It includes a pyrometer suite to measure fuel temperature profiles and a mass spectrometer to help assess fuel performance and evaluate potential material loss from the fuel element during testing. Additional diagnostic upgrades planned for NTREES include the addition of a gamma ray spectrometer located near the vent filter to detect uranium fuel particles exiting the fuel element in the propellant exhaust stream and to provide additional information of any material loss occurring during testing. Using propellant fed from gas storage trailers located external to the facility, NTREES is configured to allow continuous, uninterrupted testing of fuel elements for any desired length of time. A picture of the current NTREES primary chamber configuration is shown in Figure 3.

Figure 3. Nuclear Thermal Rocket Element Environmental Simulator.

An additional test facility associated with NTREES is an operational arc heater (Figure 4) that is capable of flowing hot hydrogen over a material or fuel sample at a hydrogen gas temperature of up to 3160 K for approximately 30 minutes. This facility could be used for the preliminary vetting of material samples. Also available is the Compact Fuel Element Environmental Tester (CFEET) capable of testing small fuel samples at high temperatures in a hydrogen environment (Figure 5).

This project will also develop a detailed understanding of the energy deposition and heat transfer processes in NTREES, along with effects on material mechanics and fluid/material interaction, to better improve future test conditions and obtain as much information as possible to accurately extrapolate non-nuclear test data to real reactor conditions.

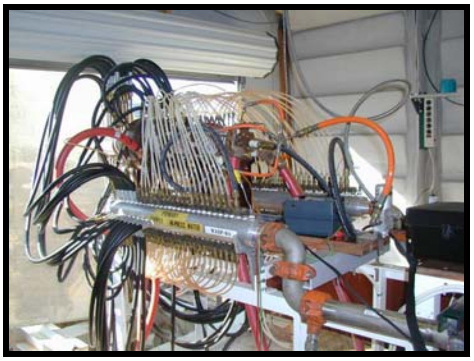


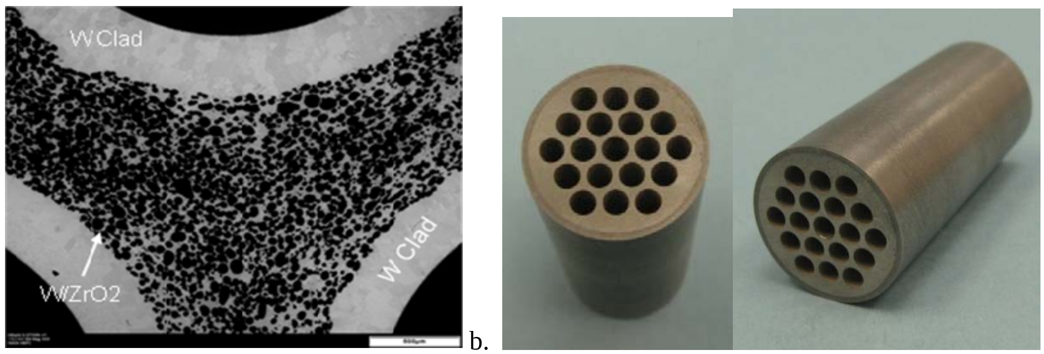
Figure 4. Arc Heater.

Figure 5. Compact Fuel Element Environmental Tester (CFEET)

B. NTP Fuel Design / Fabrication

Early fuel materials development is necessary to validate requirements and minimize technical, cost, and schedule risks for future exploration programs. The development of a stable fuel material is a critical path, long lead activity that will require a considerable fraction of program resources. The objective of the NTP Fuel Design and Fabrication task is to demonstrate materials and process technologies for manufacturing robust, full-scale CERMET and graphite fuel elements. The elements will be based on the starting materials, compositions, microstructures, and fuel forms that were demonstrated on previous programs. The development will be a phased approach to recapture key technologies and produce quality fuels. Samples will then be tested in flowing hot hydrogen to understand processing and performance relationships. As part of this demonstration task, a final full scale element test will be performed to validate robust designs. These demonstrations are necessary to enable a future fuel material down select and a potential follow on non-nuclear ground test project. A major focus of the NTP project is the use of a highly integrated NASA/DOE/Industry/Academia fuels development team. The goal is to enhance and utilize existing infrastructure and capabilities to minimize cost.

Current research at MSFC and INL is focused on developing fabrication processes for prototypical W/UO_2 cermet fuel elements. Cermets are typically formed by densification of powders using Powder Metallurgy (PM) processes. Tungsten based cermets with surrogate ceramic particles have been fabricated to near theoretical density using Hot Isostatic Press (HIP) and Pulsed Electric Current (PEC) techniques. During HIP, the cermet powders are consolidated in sacrificial containers at 2000°C and pressures up to 30 ksi. The PEC process consists of high speed consolidation of powders using DC current and graphite dies. For both HIP and PEC processing, the powder size and shape, powder loading, and processing parameters significantly affect the quality and repeatability of the final part. Figure 6 shows a typical microstructure and image of a net shape consolidated cermet part. The part is a 19 hole configuration that had uniform shrinkage during consolidation and good tolerance on the flow channel geometry.



a b.

Figure 6. a) Micrograph of a W/60 vol% ZrO_2 CERMET with integral W claddings b) Consolidated W/40 vol% HfN CERMET sample.

The nature of this initial task is rapid materials and process screening as a precursor to the detailed development that will be required to fully optimize and qualify a cermet fuel. Cermet materials and processes were demonstrated at subscale level on previous efforts, but there are significant technical and programmatic challenges for key technologies. Some of the materials and process approaches being developed to maximize performance are the size of the fuel particles and resultant shape in the consolidated part, CVD tungsten coating of spherical UO_2 particles prior to consolidation, complete surface cladding of the elements with tungsten, and additions of small amounts of fuel particle and matrix stabilization materials such as Gd_2O_3.

Significant work is also being done at ORNL to recapture graphite composite fuel materials tested in the NF-1 experiment at the end of the Rover/NERVA program. Various graphite based fuels consisting of UO_2, UC_2, or (U, Zr)C particles in a graphite matrix were tested in the Rover/NERVA program. Many of the materials were successfully demonstrated in full scale nuclear test engines. However, the fuel materials and fabrication technologies are not currently available. The NTP task is focused on developing the graphite composite extrusion and ZrC coating capabilities. The composite fuel matrix is a carbide-based ceramic fuel composition consisting of uranium carbide, zirconium carbide and graphite materials. Subscale matrix samples are being fabricated and tested to demonstrate microstructure and properties. In parallel, coating trials are being performed on short elements for hot hydrogen testing at MSFC. The goal is to partially validate recapture of coated graphite composite fuel element technology by testing a 16” segment of an element with Rover/NERVA geometry in the NTREES. Figure 7 shows images of Phoebus reactor fuels from the 1960s.

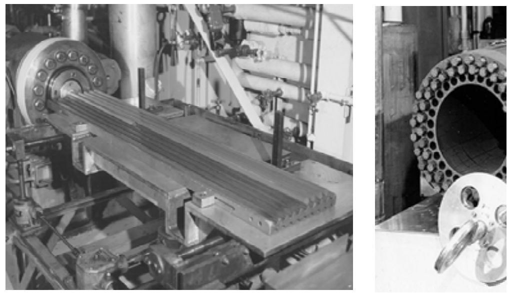
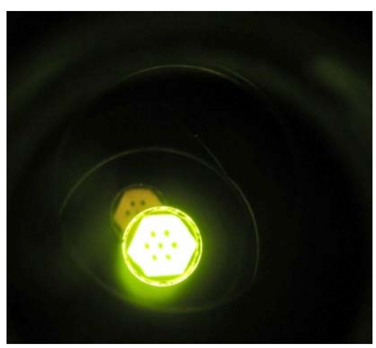


Figure 7: Images of the Rover/NERVA Phoebus Reactor fuels.

C. NTP Fuels Testing in NTREES

Testing in NTREES will range from fuel sample testing using CFEET to the testing of near-prototypic fuel elements. A primary goal of the testing is to demonstrate adequate fuel performance and to increase confidence in fuel system designs (e.g. materials, coatings, geometries) prior to potential nuclear testing. Cermet and graphite composite samples will be thermal cycle tested in a static and flowing environment. Several iterations of testing will be performed to evaluate fuel mass loss impacts from density, microstructure, fuel particle size and shape, chemistry, claddings, particle coatings, and stabilizers. Initial subscale testing is being performed in the CFEET system. The CFEET test samples are typically 0.75" across the flats and up to 3" long for solid slug and prototypic 7-hole channel configurations. The 7-hole channel configuration was chosen for CFEET screening to rapidly evaluate thermal cyclic affects on prototypic geometries from surface vaporization, diffusion/migration, and cracking. Testing has shown that fuel mass loss is significantly impacted by thermal cycling and geometry. The prototypical geometry will be much more susceptible to cracking induced migration and volatilization of the exposed fuel particles. The fuel materials and forms such as coated particles, claddings, and stabilizers being evaluated on this effort have all been demonstrated to control fuel migration and loss. The initial screening is not to determine or characterize specific modes of fuel loss or mechanisms. The intent is to verify performance improvements of the materials and processes prior to expensive full scale fabrication and testing. Posttest analysis includes weight percent fuel loss, microscopy (SEM, EBSD, and EDS), and dimensional tolerance and cracking.



Subsequent testing of full scale fuel elements will be performed in NTREES. The test samples will be based on the Rover/NERVA and ANL 200MW designs. The goal is to benchmark performance in NTREES for comparison to future materials and process improvements, alternate fabrication processes, and other fuel materials of interest. The iterative materials and process development, CFEET screening, and NTREES testing is anticipated to continue into FY 2015 and beyond. A photograph of a W / UO2 cermet sample undergoing testing in CFEET is shown in Figure 8.

D. Affordable NTP Development and Qualification Strategy

As previously noted, both the US and Russia have conducted highly successful NTR ground test and technology development programs. Although all of those programs were cancelled prior to flight, the cancellation typically

occurred because the mission requiring NTP was cancelled, not because of insurmountable issues associated with the NTR. However, if NTP is to be used, its development, qualification, and utilization must be affordable and done in a way that is technically, programmatically, and politically acceptable.

The combination of emerging technology and the relatively modest thrust needed to support a human Mars mission (if a cluster of engines is used) allows for two potential options that could be enabling for eventual utilization of NTP. First, if an emerging technology is successful it may be feasible to use low-enriched uranium (LEU) in certain NTR systems instead of highly enriched uranium (HEU). In addition to greatly increasing the political acceptance of NTP, the use of LEU will significantly increase programmatic flexibility and significantly decrease programmatic uncertainties associated with the use of HEU. These factors may reduce the cost of NTR development, qualification, and utilization by a factor of two or more.

The second option (primarily enabled by the modest thrust levels) is to fully contain the hydrogen that is exhausted during an engine ground test. Although the integrated containment system is highly sophisticated, the basic approach is to burn the hydrogen after it leaves the engine and condense the resulting steam. Any fission products released from the fuel during testing would be contained in the water and the overall containment system. Standard techniques would then be used to perform any required decontamination. An initial schematic of the fully contained exhaust system is show in Figure 9.

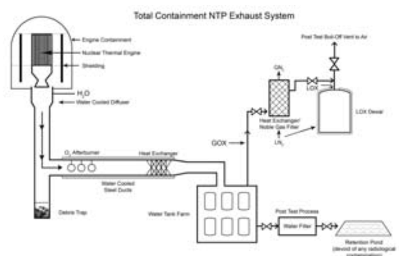


Figure 9. Option for Fully Containing NTR Exhaust During Ground Testing.

In addition to ground testing a full scale NTP engine, a flight demonstration is being investigated to help qualify the engine system and possibly used by a potential customer for a robotic mission. The flight demonstration would use the same NTR engine being developed to support a human Mars mission, but would have the option of running de-rated either in terms of thrust or Isp. The flight demo would also allow operation of a high area ratio nozzle, which is not possible in ground testing. Advanced instrumentation and robotics is being investigated to use on the NTP flight demo for inspection of the major engine components. Figure 10 shows similar instrumentation previously used on the space shuttle for inspecting the orbiter following launch.

The flight demonstration also starts preparing the launch facilities for the safety and security of launching a nuclear reactor under all potential abort scenarios. Some abort scenarios require the engine to be tested under those abort conditions for acceptability. A nuclear safety review and launch approval process is required and shown in Figure 11. The launch approval process could take up to 5 years to get final approval and needs to be accounted for in the overall development plan. Both strategies for ground testing and flight demonstration appear to show promise.

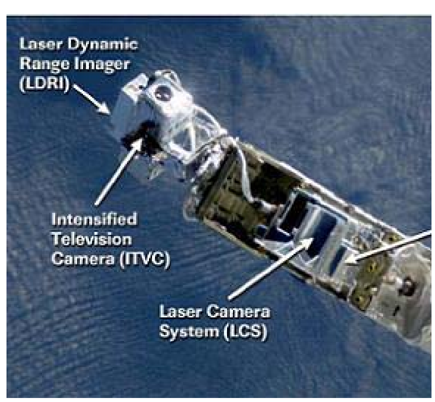


Figure 10. JSC Robotic Instrumentation.

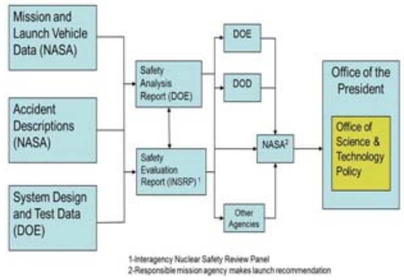


Figure 11. Nuclear Safety Review and Launch approval Process

VI. Conclusion

The potential capability of NTP is game changing for space exploration. A first generation NTP system could provide high thrust at a specific impulse on the order of 900 s, roughly double that of state of the art chemical engines. Near-term NTP systems would provide a foundation for the development of significantly more advanced, higher performance systems. Although the guidance, navigation, and control of NTP systems may have some unique aspects, there do not appear to be any showstoppers. For NTP to be utilized, an affordable development and qualification strategy must be devised.